Reproducibility of Tube Current Modulation CT scans and Radiation Dose for Cardiac PET/CT

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Boston, MA
• Radiation Dose in Myocardial Perfusion Imaging
  - Dose reduction

• Role of CT in Quantitative PET/CT

• Reproducibility of tube current modulation CT
  - Automatic exposure control in Low-dose CT of PET/CT
  - Retrospective review of dose reports
NCRP Report No.160: Exposure of the US Population

Effective dose per capita:
- Early 1980s: 3.6 mSv
- 2006: 6.2 mSv

Medical radiation:
- Early 1980s: 0.53 mSv
- 2006: 3.0 mSv
### Estimated Number and Collective Effective Doses from Radiologic and Nuclear Medicine Procedures in the United States for 2006

<table>
<thead>
<tr>
<th>Type of Procedure</th>
<th>No. of Procedures in Millions</th>
<th>Percentage of Total No. of Procedures</th>
<th>Collective Effective Dose (person-sievert)</th>
<th>Percentage of Collective Dose from Procedures</th>
<th>Per-Capita Dose (mSv)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diagnostic radiographic and fluoroscopic studies*</td>
<td>293</td>
<td>74</td>
<td>100 000</td>
<td>11</td>
<td>0.33</td>
</tr>
<tr>
<td>Interventional procedures</td>
<td>17</td>
<td>4</td>
<td>128 000</td>
<td>14</td>
<td>0.43</td>
</tr>
<tr>
<td>CT scanning</td>
<td>67</td>
<td>17</td>
<td>440 000</td>
<td>49</td>
<td>1.47</td>
</tr>
<tr>
<td>Nuclear medicine studies</td>
<td>18</td>
<td>5</td>
<td>231 000</td>
<td>26</td>
<td>0.77</td>
</tr>
<tr>
<td>Total</td>
<td>395</td>
<td>100</td>
<td>899 000</td>
<td>100</td>
<td>3.01</td>
</tr>
</tbody>
</table>

CT + NM: account for 22% of all procedures, but deliver 75% of the collective ED.

Mettler F A et al. Radiology 2009;253:520-531

<table>
<thead>
<tr>
<th>Procedure</th>
<th>Average Effective Dose (mSv)</th>
<th>Annual Effective Dose (mSv) per person</th>
<th>Proportion of Overall Effective Dose From Medical Imaging Procedures</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Myocardial perfusion imaging</td>
<td>15.6 (^b)</td>
<td>0.540</td>
<td>22.1%</td>
</tr>
<tr>
<td>2. Computed tomography (CT) of the abdomen</td>
<td>8</td>
<td>0.446</td>
<td>18.3%</td>
</tr>
<tr>
<td>3. CT of the pelvis</td>
<td>6</td>
<td>0.297</td>
<td>12.2%</td>
</tr>
<tr>
<td>4. CT of the chest</td>
<td>7</td>
<td>0.184</td>
<td>7.5%</td>
</tr>
<tr>
<td>5. Diagnostic cardiac catheterization</td>
<td>7</td>
<td>0.113</td>
<td>4.6%</td>
</tr>
<tr>
<td>6. X-ray of the lumbar spine</td>
<td>1.5</td>
<td>0.080</td>
<td>3.3%</td>
</tr>
<tr>
<td>7. Mammography</td>
<td>0.4</td>
<td>0.076</td>
<td>3.1%</td>
</tr>
<tr>
<td>8. CT angiography of the chest (non-coronary)</td>
<td>15</td>
<td>0.075</td>
<td>3.1%</td>
</tr>
<tr>
<td>9. Upper GI series</td>
<td>6</td>
<td>0.058</td>
<td>2.4%</td>
</tr>
<tr>
<td>10. CT of the head/brain</td>
<td>2</td>
<td>0.049</td>
<td>2.0%</td>
</tr>
</tbody>
</table>

Myocardial Perfusion Imaging is the single medical test with the highest radiation burden to the US population → 22% of cumulative effective dose from medical sources
Multiple MPI testing

AJ Einstein et al. JAMA 2010; 304((9): 2137-2144

- 1097 consecutive patients undergoing MPI in 2006 at Columbia U. Medical center were reviewed.

- evaluated all preceding medical imaging procedures involving ionizing radiation undergone beginning October 1988, and all subsequent procedures through June 2008.

- Many patients undergoing a single cardiac imaging study will undergo many procedures involving ionizing radiation

  → median of 15 procedures (6 – 32 IQR) involving radiation exposure

- 31% of patients received cumulative estimated effective dose > 100 mSv

- 39% of patients had multiple MPIs. → cumulative effective dose of 121 mSv
Typical Effective Doses From Cardiac Imaging Procedures

Chest PA x-ray: ~0.02 mSv

Equivalent to 1,200 chest x-ray

Myocardial perfusion imaging (MPI)

- Radionuclide myocardial perfusion imaging (MPI) has become a major tool in the noninvasive evaluation of coronary artery disease (CAD)
- MPI test: to test how well blood flows through the heart muscle (perfusion) → assess the overall function
- Can show areas of the heart muscle that aren’t getting enough blood flow → assess damage
- MPI doesn’t show the heart arteries themselves, but can tell if any heart arteries are blocked and how many.
- The greatest strength of MPI is its established value for risk assessment. → The extent and severity of ischemia and scarring on SPECT and PET MPI are powerful predictors of future cardiovascular events

http://www.snmmi.org/AboutSNMMI/Content.aspx?ItemNumber=986
## Radiopharmaceuticals (tracers) for MPI

<table>
<thead>
<tr>
<th>Protocol</th>
<th>Injected activity (mCi)</th>
<th>Dose (mSv/mCi)</th>
<th>Effective dose (mSv)</th>
</tr>
</thead>
<tbody>
<tr>
<td>99mTc – sestamibi (6 hrs)</td>
<td>10 (rest) 20 - 30 (stress)</td>
<td>0.315</td>
<td>12.5</td>
</tr>
<tr>
<td>201TI-stress (73 hrs)</td>
<td>2 - 4</td>
<td>8.51</td>
<td>22</td>
</tr>
<tr>
<td>99mTc-tetrofosmin</td>
<td>10 (rest) 20 - 30 (stress)</td>
<td>0.248</td>
<td>9.3</td>
</tr>
<tr>
<td>Dual isotope (TI-Tc)</td>
<td>3.5 25</td>
<td>29.2</td>
<td></td>
</tr>
<tr>
<td>82Rb (75 sec)</td>
<td>50 50</td>
<td>0.027</td>
<td>2.7</td>
</tr>
<tr>
<td>13N-ammonia (10 min)</td>
<td>15 15</td>
<td>0.100</td>
<td>3.0</td>
</tr>
<tr>
<td>15O-water (122 sec)</td>
<td>30 30</td>
<td>0.039</td>
<td>2.4</td>
</tr>
<tr>
<td>18F-FDG (110 min)</td>
<td>10</td>
<td>0.703</td>
<td>7</td>
</tr>
</tbody>
</table>

- activity administered
- physical characteristics of radionuclide
- biological characteristics of the pharmaceutical
Our effort to reduce radiation dose from MPI

<table>
<thead>
<tr>
<th>Method</th>
<th>Radiation Dose (ED)</th>
<th>Procedure Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>MPI SPECT</td>
<td>~12.1 mSv</td>
<td>Tc-99m Sestamibi 10mCi rest + 30mCi stress</td>
</tr>
<tr>
<td>DSPECT system</td>
<td>~6 mSv</td>
<td>Tc-99m Sestamibi ~5 mCi rest + 15 mCi stress</td>
</tr>
<tr>
<td>N13 PET/CT scans</td>
<td>~4.6 mSv</td>
<td>N13-ammonia 20 mCi rest + 20 mCi stress</td>
</tr>
</tbody>
</table>

Since 2007

Rb-82 PET/CT MPI (ED ~ 6.0 mSv) (2004-2011)

Since 2011
\( \text{\(^{13}\text{N}-\text{ammonia cardiac PET/CT}\)} \)

- Produced onsite using a cyclotron: \( ^{1}\text{H} + ^{16}\text{O} \rightarrow ^{13}\text{N} + ^{4}\text{He} \)
- \( ^{13}\text{N} \): positron emitter (T1/2 = 10 min): \( ^{7}\text{N} \rightarrow ^{6}\text{C} + \beta^+ + \nu^0 \)
- **Positron-Electron Annihilation**

The positrons themselves are not directly detected to make images

Conversion of rest mass (\( \beta^+ & e^- \)) into radiation (511keV)
The most important physical effect in PET imaging:

- Photons are absorbed or scattered, and not being detected
- The number of detected photons << the number of emitted photons

For quantitative imaging, the lost photons need to be estimated to calculate the original number of emitted photons

→ attenuation correction
Non-uniform liver
Enhanced skin uptake
Hot lungs
Non-uniform liver

SC Moore and MA Park, PET and PET/CT Physics, Instrumentation and Artifacts in A Case-Base Approach to PET/CT in Oncology by V. Gerbaudo Cambridge University Press, 2012
X-ray CT imaging

- Detect transmitted x-rays while x-ray tube and detectors rotate
- Build 3D images from the transmitted x-rays
- Each voxel on CT image represents tissue density in relation to its x-ray absorption (attenuation coefficient)

\[ N_i = N_0 e^{-(\mu_1 w_1 + \mu_2 w_2 + \mu_3 w_3 + \ldots + \mu_N w_N)} = N_0 e^{-(\mu_1 + \mu_2 + \mu_3 + \ldots + \mu_N) w} \]
Replace the attenuation coefficient calculated for each voxel of the reconstruction matrix with an integer (CT number or HU)

\[ HU = \frac{\mu_{\text{voxel}} - \mu_{\text{water}}}{\mu_{\text{water}}} \times 1000 \]

The attenuation coefficient, \( \mu \), is energy dependent, \( \mu(E) \).
Bremsstrahlung spectrum (x-rays) vs. 511keV photons

Different attenuation coefficient for different energies
PET-CT protocol

- Pharmacologic stress drug: adenosine, regadenoson, or dobutamine
Conversion of CT images to attenuation map

Original CT
512x512

Intermediate CT
128 x 128

Attenuation coefficient map
(μ-map)
128 x 128
N13-Ammonia cardiac PET/CT

Normal perfusion

With perfusion defects

stress rest

Normal perfusion
Gated cardiac PET/CT
Dynamic cardiac PET/CT

Global Results

<table>
<thead>
<tr>
<th>Region</th>
<th>MC Str</th>
<th>MC Rst</th>
<th>MC Str</th>
<th>MC Rst</th>
<th>Reserve</th>
</tr>
</thead>
<tbody>
<tr>
<td>LAD</td>
<td>79 %</td>
<td>78 %</td>
<td>1.29</td>
<td>0.91</td>
<td>1.42</td>
</tr>
<tr>
<td>LCX</td>
<td>75 %</td>
<td>68 %</td>
<td>1.31</td>
<td>0.82</td>
<td>1.60</td>
</tr>
<tr>
<td>RCA</td>
<td>81 %</td>
<td>84 %</td>
<td>1.10</td>
<td>0.84</td>
<td>1.32</td>
</tr>
<tr>
<td>TOT</td>
<td>78 %</td>
<td>75 %</td>
<td>1.23</td>
<td>0.86</td>
<td>1.43</td>
</tr>
</tbody>
</table>

Algorithm (MC Str): INVIA N-13 ROI 1:1
Algorithm (MC Rst): INVIA N-13 ROI 1:1

MC Str Time Activity Curves

MC Rst Time Activity Curves
Motivation

- Automatic exposure control (AEC) is widely used in x-ray imaging.
- AEC automatically adapts the Tube Current (mA) or Tube Potential (kVp) according to patient attenuation to achieve a specified image quality.
- AEC are particularly useful for non-homogeneous scan regions or for body parts that are not uniform in size.

Studies have documented substantial CT radiation dose reductions with use of AEC in adult as well as pediatric patients, ~ 20-50%.

Precision or reproducibility of AEC has not been reported in human subjects.

- None has been reported in human subjects, to our knowledge.
Evaluation of AEC CT scans

• Previously, all evaluations were done on phantoms
e.g., 2014 annual meeting, AAPM-SU-E-I-91: Reproducibility in Prescribed Dose in AEC CT Scans Due to Table Height, Patient Size, and Localizer Acquisition Order, by J Winslow¹, L Hurwitz¹, O Christianson¹ and E Samei¹

• Cardiac same day rest/stress PET/CT offers a unique opportunity to assess the reproducibility of the dose modulation technique
• the same patient is scanned in one bed position with the same parameters on the same scanner within the same day.

\[\text{PET}_1 (20 \text{ min})\]
\[\text{CT}_1\]
\[T=0\]

\[\text{PET}_2 (20 \text{ min})\]
\[\text{CT}_2\]
\[T=60 \text{ min}\]

15-20mCi N13

Pharmacologic stress

15-20mCi N13
CT scan parameters

- GE discovery STE or RX PET/CT system with 64 slices VCT
- 64 x 0.625 mm collimation (4 cm beam width)
- 0.984 pitch,
- 0.5 sec rotation time,
- 120 kVp tube voltage.
- Noise Index (NI) was set at 50 for **Smart mA** technique
- mA: tube current of min=10 and max=200 mA.
- **2.5 mm** and 5 mm slice thickness,

- PET scan length: 15.7 cm – fixed for one bed position, enough to include the heart in the FOV.
- Need the same scan length of CT for attenuation correction.

- Overranging in helical scan: extra rotation is required at beginning and end of imaged volume to avoid having incomplete data set for reconstruction.
  \[\text{CT scan length} \approx 19.4 \text{ cm}.\]
For both rest and stress CT scans,

- Head first,
- Both arms up, if possible
- Heart was placed in the center of the field
- Patient was positioned laterally at the center of the gantry
- Table height was also adjusted for centering the patient.
Example of AEC (Smart mA)

- Tube current modulation based on a prescribed image quality, e.g., Noise Index

- The noise index value is approximately equal the standard deviation in the central region of the image when a uniform phantom (with the patient’s attenuation characteristics) is scanned and reconstructed using the standard reconstruction algorithm.

For example, NI = 20 → Standard deviation of HU in soft tissue ~ 20.

- Increasing NI → increase image noise, degrade image quality, and decrease CTDIvol.
**Study cohort & data**

- A retrospective review of displayed CT indices for **401** adult patients who underwent rest and stress N-13 PET/CT within 24 hours over a one year period (1/1 – 12/31, 2014)

- Scans were acquired on GE PET/CT DSTE or DRX systems with an automatic tube current modulation technique (Smart mA) turned on

- A total of **362** patients over one year period with dose reports available

**Parameters recorded**

- Body Mass Index (BMI) = weight / height$^2$ (kg/m$^2$)
- Scan time
- CTDIvol (mGy)
- DLP (mGy.cm)
- kVp
- Table height (from DICOM)
- Reference slice number
- Effective diameter on the reference slice
Axial shift between two scans using the Reference slice

same scan length

scan1

Axial position change

scan2
Reference slice with division of trachea (carina)

Effective diameter is measured on the reference slice.

Effective diameter = $\sqrt{AP \times LAT}$
Results

- 403 reviewed, Jan-Dec, 2014
- 42 patients: the lower limit of the dose range (10mA) in either or both scans

Exclusions

- different kVp
- Either or both arms in the scan field
- Missing dose report

Final number: 297 complete studies
Arms in the field of view

BMI = 25  
CTDvol = 0.88 mGy  

BMI = 25  
CTDvol = 1.72 mGy
### Results: mA profile

**Slice position:**

<table>
<thead>
<tr>
<th>CTDI\textsubscript{vol} (mGy)</th>
<th>rest</th>
<th>stress</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.71</td>
<td>1.70</td>
<td></td>
</tr>
</tbody>
</table>

**BMI = 29.5**

Eff. Dia = 31.5 cm

<table>
<thead>
<tr>
<th>CTDI\textsubscript{vol} (mGy)</th>
<th>rest</th>
<th>stress</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.60</td>
<td>3.89</td>
<td></td>
</tr>
</tbody>
</table>

**BMI = 40.0**

Eff. Dia = 39.1 cm
## Results: Multiple MPI PET/CT scans

<table>
<thead>
<tr>
<th>Pt-1</th>
<th>CTDIvol (mGy)</th>
<th>BMI (kg/m²)</th>
<th>Eff. Dia (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>rest</td>
<td>stress</td>
<td></td>
</tr>
<tr>
<td>May</td>
<td>4.04</td>
<td>4.25</td>
<td>37.8</td>
</tr>
<tr>
<td>June</td>
<td>3.05</td>
<td>3.76</td>
<td>37.8</td>
</tr>
<tr>
<td>Sept</td>
<td>3.76</td>
<td>4.38</td>
<td>37.2</td>
</tr>
</tbody>
</table>

Mean: $3.87 \pm 0.48$

CV% = 12.3%

<table>
<thead>
<tr>
<th>Pt-2</th>
<th>CTDIvol (mGy)</th>
<th>BMI (kg/m²)</th>
<th>Eff. Dia (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>rest</td>
<td>stress</td>
<td></td>
</tr>
<tr>
<td>Early April</td>
<td>1.22</td>
<td>1.36</td>
<td>27.6</td>
</tr>
<tr>
<td>Late April</td>
<td>1.18</td>
<td>1.19</td>
<td>26.5</td>
</tr>
<tr>
<td>June</td>
<td>1.23</td>
<td>1.33</td>
<td>27.7</td>
</tr>
</tbody>
</table>

Mean: $1.25 \pm 0.08$

CV% = 7.5%
BMI vs. Effective diameter

![Graph showing BMI vs. Effective diameter]
Results: CTDIvol for CT scan 1

- CTDIvol ≤ 2.1 mGy → N = 204
- CTDIvol > 2.1 mGy → N = 93
# Results

<table>
<thead>
<tr>
<th></th>
<th>BMI (kg/m(^2))</th>
<th>Effective diameter (cm)</th>
<th>Scan length (cm)</th>
<th>Time between two scans (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>mean</td>
<td>31.72</td>
<td>32.72</td>
<td>19.64</td>
<td>63.19</td>
</tr>
<tr>
<td>stdev</td>
<td>9.09</td>
<td>4.60</td>
<td>0.04</td>
<td>12.94</td>
</tr>
<tr>
<td>median</td>
<td>30.11</td>
<td>32.04</td>
<td>19.63</td>
<td>60.00</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Effective diameter (cm)</th>
<th>Scan length (cm)</th>
<th>Displayed CTDI (mGy)</th>
<th>Fixed parameters (before 2013)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CT scan 1</td>
<td>32.72 ± 4.60</td>
<td>19.64 ± 0.04</td>
<td>1.95 ± 1.40</td>
<td>2.1 mGy</td>
</tr>
<tr>
<td>CT scan 2</td>
<td>32.77 ± 4.63</td>
<td>19.64 ± 0.04</td>
<td>1.97 ± 1.42</td>
<td>2.1 mGy</td>
</tr>
</tbody>
</table>
### BMI and AEC reproducibility

<table>
<thead>
<tr>
<th></th>
<th>mean BMI</th>
<th>mean CTDIvol</th>
<th>stddev CTDIvol</th>
<th>min CTDIvol</th>
<th>max CTDIvol</th>
<th>mean %diff</th>
</tr>
</thead>
<tbody>
<tr>
<td>BMI&gt;30 (N=165)</td>
<td>37.73</td>
<td>2.73</td>
<td>1.51</td>
<td>0.86</td>
<td>9.43</td>
<td>9.03</td>
</tr>
<tr>
<td>BMI&lt;30 (N=155)</td>
<td>26.05</td>
<td>1.27</td>
<td>0.67</td>
<td>0.84</td>
<td>6.02</td>
<td>6.66</td>
</tr>
<tr>
<td>all</td>
<td>32.08</td>
<td>2.04</td>
<td>1.41</td>
<td>0.84</td>
<td>9.43</td>
<td>7.88</td>
</tr>
</tbody>
</table>

\[
\text{%diff} = \frac{|CTDI_2 - CTDI_1|}{\left(\frac{CTDI_1 + CTDI_2}{2}\right)} \times 100
\]

The AEC reproducibility was worse with higher BMI.
Results: Table height and % Diff CTDI

N = 297

$\Delta$ (Table height), mm

Table moved down  Table moved up
Same axial position (N=54)

$R^2 = 0.5962$
Same table height (N=36)
Summary

• The ED for rest-stress N13 ammonia PET/CT scan is ~ 4.6 mSv. Even with the additional dose from the CT scan, it is a lot lower than that for cardiac SPECT.

• Evaluation of reproducibility of tube current modulation CT, first time in human subject, to our knowledge

• For patients scanned the same day on the same scanner using automatic tube current modulation, dose was reproducible within 7.9 % of average percent difference

• Reproducibility was somewhat worse with higher BMI.

• Centering the patient in the gantry is important in reducing the CT dose